

To be presented at 1988 ASME Winter Annual Meeting.

A FRAMEWORK FOR ANALYSIS OF A BRACING MANIPULATOR WITH STAGED POSITIONING

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ABSTRACT

The concepts of staging and bracing are introduced with the specific example of a bracing manipulator. Staging describes the operational strategy which divides the positioning procedure into two or more levels to maximize the efficiency of the total positioning system. A bracing manipulator can be operated like a two-stage motion system.

The bracing effect is evaluated from the view point of reduction of positioning uncertainty. Uncertainty sources in the manipulator, and the reduction of the positioning uncertainty by geometric bracing constraints are analyzed. The framework of controlling a bracing manipulator will be discussed with the hybrid position and force control.

INTRODUCTION OF STAGING IN POSITIONING

There is a vast literature in the area of controlling robot manipulators (both rigid and flexible), AGVs, and other transfer machines. Their ultimate goal is maximizing the performance of an individual machine by obtaining better positioning accuracy and high speed. A positioning task is typically performed by a combination of machines each of which has its own positioning uncertainty. The use of a combination of different machines requires a new concept and a new technology to obtain the best overall performance satisfying the restrictions of a task. The concept of staging in positioning shown in Fig. 1 is defined as the use of different degrees of freedom by dividing the positioning procedure into several levels for different phases of a positioning task to meet the total motion requirement.

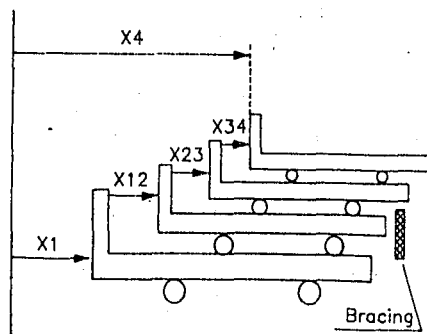


Figure 1. Staged Positioning with Multi D.O.F.

The following three examples illustrate this concept. First, an object is picked up by human or automated storage and retrieval system (ASRS), transported by human, conveyer belt, fork lift, vehicle, or train to another location, then unloaded and stored in another warehouse by man or ASRS. This general transportation can be regarded as a positioning job which is divided into several steps. For each step, a different machine or human performed the job to meet the restrictions of the task. A human's positioning motion is a second example. He moves his body a certain distance first, moves an arm to locate the object approximately at the desired position, braces his wrist, and moves his fingers to get the exact position by compensating errors with the feedback of vision and force. Finally, in an automated production line a combination of AGV's and robots or can be used for material handling. The transportation/positioning system is composed to meet the requirements of the job such as transfer range, speed, number of parts, and positioning accuracy.

Bracing Strategy

When the positioning motion is divided into several stages, it is easy to reduce the positioning uncertainty by including a geometric constraint condition referred to as bracing between two stages as shown in Fig.1. Therefore, the bracing strategy is an important aspect in the concept of staging in positioning.

There are increasing amounts of literature on the control of flexible arms to reduce their vibrations [29,30,31]. However, there are limitations on controlling all the vibration modes because of approximate dynamic modeling and real time control limitations. One application of the bracing strategy is to reduce or eliminate vibrations and other random errors. The human bracing his wrist for exact positioning is a good example of bracing strategy: the positioning uncertainty of the arm motion is reduced by the constraints of the braced surface.

The bracing method can be applied to AGV systems to reduce positioning uncertainty. The position and orientation of the AGV is estimated from wheel rotations and the steering angle [1,2,3]. Even though the AGV continuously corrects its position by sensing targets along the path, the final position still has some uncertainty [4,5]. If a bar in Fig.2, whose position is exactly known, is installed in front of the spot where the AGV should stop, the constraint enforces near exact position in one direction. As a result, the uncertainty in that direction is reduced to nearly zero. Uncertainty in the other direction can be reduced and can be predicted more precisely by this constraint.

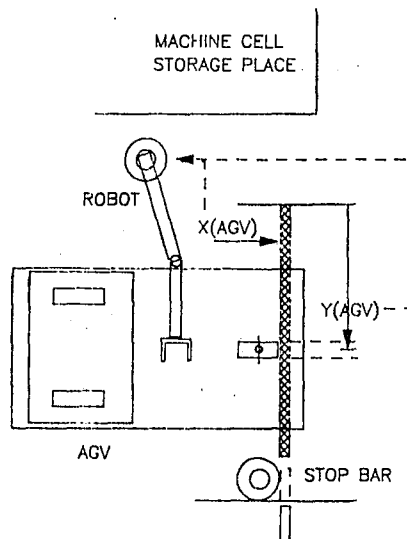


Figure 2. Bracing Strategy Applied to AGV.

ANALYSIS APPROACH

The Bracing Manipulator

The bracing strategy can be used with a robot manipulator employing the operational strategy of staging in positioning. Several authors have suggested the use of a bracing device to attach the end effector of a manipulator to the working surface. In 1983, Moore and Hogan [6] introduced a part referenced manipulator concept with a mobile drilling end effector which modified the end point behavior by coupling it

to the environment mechanically. Asada and West [7] proposed a tool guide mechanism for the grinding robot which increases the stiffness of a robot end effector to bear the vibratory interaction force.

A different bracing strategy concept was proposed by Book, et al [8] and applied to the lightweight arm. The large flexible arm moves into a certain position, and braces against the work piece or a static structure. Then the precise motion is performed by a small arm at the end of the large arm.

West and Asada [9] analyzed kinematics of a manipulator braced against the work surface within the framework of Mason [10]. They also described the mechanical advantage of a bracing manipulator. The high load capacity of the end effector that can be obtained by bracing can make it effective for machining. West [11] presented the kinematics and statics of the bracing device which he referred to as a jig hand, and the hybrid position and force control for the constrained motion control of a commercial industrial robot in his thesis. He emphasized the mechanical advantage of high force transmission ratio, high stiffness, and improved accuracy because of part reference as the advantages of a bracing arm.

If the current industrial robot concept, which is based on the assumptions of rigid links and negligible random errors, is extended to a robot with a large working space, the important error sources are different. Error sources such as sensor resolution, gear backlash, joint flexibility, and link flexibility, which are negligible in current industrial robots, will be significant for large robots. In the case that a large working space is required with small tolerance of positioning error, the arm of the manipulator should be long. Due to its large structure, a small error source such as sensor resolution error, or gear backlash can cause large errors between the actual position and desired position of the end point. Moreover, its weight will be limited by the capacity of actuators, so that poor rigidity of the arm can induce flexible vibrations at each link. To satisfy all the requirements positioning motion is divided into two stages. For the first stage of motion the large arm can be used for the motion of relatively long distance with high speed, but the end point position of the large arm has large uncertainty. This uncertainty will be propagated to the error of the small arm end point and may exceed the tolerance of the positioning error of the task. To reduce the uncertainty of the large arm by giving geometric constraint conditions, the end point of the large arm, which can be thought of as a wrist, is braced on a surface or a work piece. For the second stage of motion a small arm, which is attached at the end of the relatively flexible large arm, is used to compensate for the errors and accomplish fine motions. This is called a bracing manipulator. Therefore, a bracing manipulator is defined as a two-stage motion manipulator which has a large arm, a wrist, and a small arm as shown in Fig.3.

The bracing support for the small arm allows it to have a higher bandwidth control system, since this bandwidth is limited by the natural frequency. High bandwidth is also consistent with high precision.

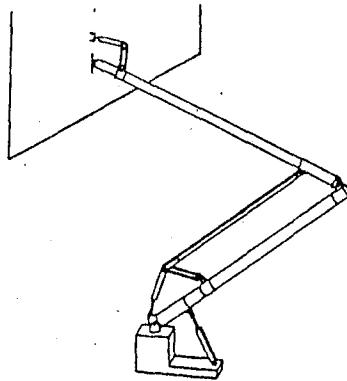


Figure 3. A Bracing Manipulator.

Uncertainty Analysis of a Manipulator

To analyze the effect of a bracing manipulator in reduction of positioning uncertainty, uncertainty sources of a manipulator are studied. The error sources and the calibration techniques for kinematic errors of a manipulator were surveyed by many authors. Simunovic [12] listed the sources of uncertainty in automated assembly with a serial link manipulator. He considered not only the error sources of the manipulator but also the error in the position of the object to be grasped and the uncertainties of the position of the working environment. The characteristics of each uncertainty were not studied in detail. Current industrial robots were investigated by Warnecke, et al [13]. An assessment and comparison of the accuracy of positioning were presented. The test of the robot accuracy was classified into static, dynamic, kinematic, and thermal behavior. At the Physikalisch-Technische Bundesanstalt, several versions of KRS

(Kinematic Reference Standards) were constructed to measure the errors with standardized methods [14]. In this research, Kuzmann and Waldele showed the application result of KRS on CMM (Coordinate Measuring Machine), and classified errors into systematic errors and random errors. In response to the need of industry for the standardization of robot performance measurement, Lau and Hocken [15] of NBS suggested standard definitions of terminologies about accuracy evaluation and standard test procedure, but also summarized the classification of error sources by physical causes.

Error sources have been classified from different view points by several authors [12,13,14,15]. The importance of each error will depend on the robot manipulator and its task. In this research, the errors are classified by the characteristics of behavior as follows:

- Geometric error: link dimension errors
misalignment of links
origin shift, misalignment of
a robot base

These errors can be estimated and compensated by several calibration techniques.

- Random errors: sensor resolution
mechanical error such as gear
backlash, bearing looseness

These errors cannot be reduced by the control algorithm, but they can be reduced by bracing constraints.

- Vibration: flexible beam vibration
flexible joint vibration

Most industrial robots are assumed to be rigid, so that the uncertainty due to these vibrations is not considered. But they become more important as the arms become larger and/or lighter. Even though these flexible vibrations can be reduced by advanced control schemes [30,31], it may not be satisfactory in the multi-link case.

- Systematic but varying error:
static deflection
thermal error

Static deflection is dependent on load and the arm configuration. The thermal error results from the environmental temperature. They can be compensated by the deterministic relation between load, temperature and deflection and also reduced by bracing constraints.

Since geometric errors and static deflection, and thermal errors can be compensated by proper techniques, these will not be considered in this research. The bracing strategy seems to be effective to reduce random errors and flexible vibrations.

The statistical model of the random positioning errors of a manipulator which cannot be eliminated by calibration was developed by Kumar and Waldron [16]. The surface curves of equal positioning accuracy of the end effector were generated by that statistical model and plotted. Mooring and Tang [17] presented an algorithm for the identification of the axis position error and orientation error for a six revolute joint robot without distinguishing random errors of systematic errors. A kinematic error model, which is based on differential changes of coordinate frames of Paul [18] due to kinematic errors, was developed by Wu [19]. This error model is a generalization of the manipulator jacobian with respect to four D-H kinematic parameters. He showed the relationship between cartesian errors of the end effector and kinematic parameter errors in each link using a linear model.

Hayati [20] proposed a general method for the estimation of the geometric parameter errors of a manipulator, claiming the positioning errors cannot be represented by D-H four parameter errors in the case of two consecutive parallel axes. Veitschegger and Wu [21] modified their kinematic error model based on D-H link geometric parameters to be valid in the special case of two consecutive parallel joints by adding one more rotational transformation matrix to the D-H transformation matrix.

Even though most authors modeled random errors stochastically, a different approach was presented by Whitney, et al [22]. In this paper, nongeometric errors, such as gear transmission error, joint compliance error, and gear backlash error were modeled with deterministic functions, and those error models were applied to a forward calibration method.

Azardivar [23] claimed that the main cause of robot hand's positioning error are the errors in joint variables and errors in link parameters. In his work, it is assumed that the effect of link parameter errors can be compensated by a proper calibration, and the joint positioning error can be decomposed into the biased deterministic error and randomly induced error. Only the effect of random errors in joint variables on the accuracy of positioning was studied using stochastic models.

As an error analysis tool, Wu's error model equations [19,21] which generalizes the manipulator jacobian [18] is considered because of its well structured form. The equations are as following :

Figure 4. A Planar Bracing Manipulator Constrained on the Bracing Plane.

$$J_c \delta \theta_c = 0$$

$$\delta \theta_c = [\delta \theta_{1c}, \delta \theta_{2c}, \delta \theta_{3c}, \delta \theta_{4c}]^t$$

$$\delta \theta_c = N(J_c)$$

The constraint condition of the random error vector $\delta \theta_c$ can be determined from the assumption that constrained error bound cannot exceed the unconstrained original error bound.

$$|\delta \theta_i|_c \leq |\delta \theta_i|_{\max} \quad i = 1, 2$$

Then, the random vector value of the closed loop can be applied to calculate the uncertainty of an end point of the small arm.

$$\delta X_o = J_o \delta \theta_o$$

$$\delta \theta_o = [\delta \theta_{1c}, \delta \theta_{2c}, \delta \theta_{3c}, \delta \theta_{4c}]^t$$

If the reduction ratio of uncertainty is defined by the magnitude of a random vector, the effectiveness of bracing can be represented with the following relation.

$$R = \frac{|\delta X_o|_{\text{unbraced}}}{|\delta X_o|_{\text{braced}}}$$

The reduction of uncertainty by bracing for a 4 link planar manipulator is kinematically analyzed as shown in Fig. 5. It is assumed that each joint angle has uniform and independent positioning uncertainty which could result from sensor resolution or gear backlash, for example. The bracing constraint reduces the positioning uncertainty of the bracing wrist $\{\delta x_w, \delta y_w\}$ and as a consequence the end point positioning uncertainty $\{\delta x_e, \delta y_e\}$ is greatly reduced.

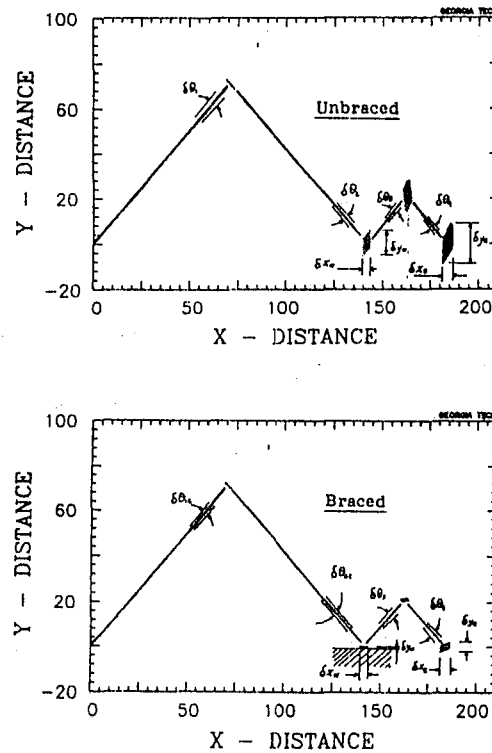


Figure 5. Positioning Uncertainty of a Bracing Manipulator.

The effectiveness of the bracing strategy in reducing vibration and random errors is experimentally shown in Fig. 6, too. The acceleration, which was measured at the large arm end point of a bracing

manipulator shown in Fig. 3, is analogous to the positioning uncertainty of the bracing wrist $\{\delta x_w, \delta y_w\}^T$ of Fig. 5. Great reduction of positioning uncertainty in y-direction was observed as it was predicted kinematically in Fig. 5.

Force Control

The assembly task or the task of contacting a stationary surface cannot be performed satisfactorily by a rigid manipulator with very stiff positioning servos. It is often jammed or damaged by very small positioning errors which can produce very large contact forces.

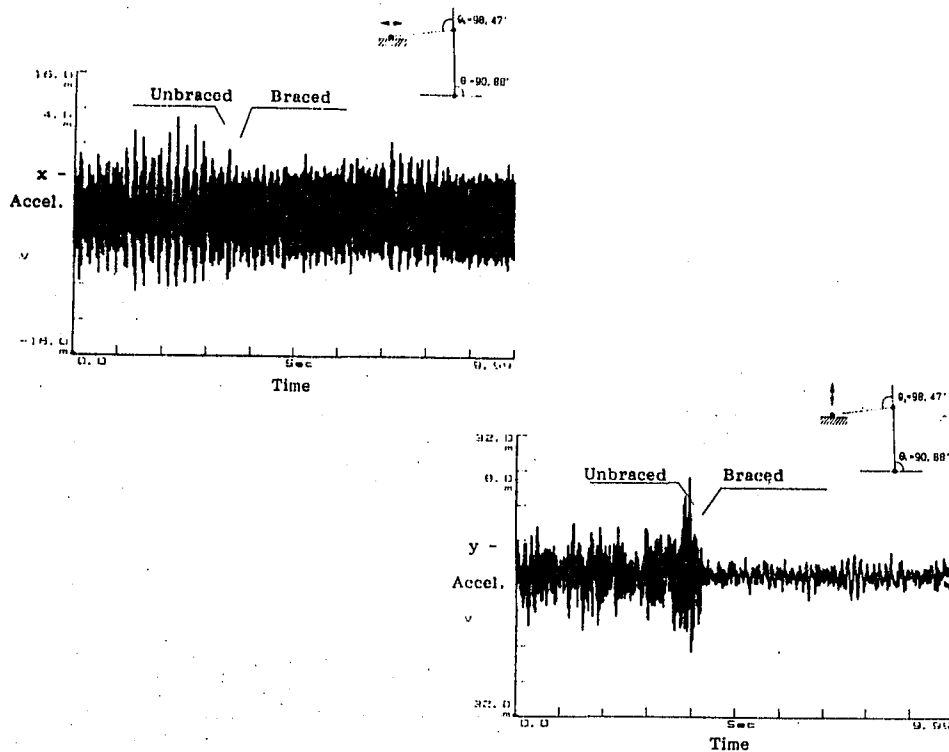


Figure 6. Experimental Results showing effect of bracing on the RALF a large, light-weight arm. a) Parallel to bracing surface, b) perpendicular to bracing surface.

C. S. Draper Laboratory [24] developed the RCC (remote center compliance) device which has some passive compliance to allow successful mating of parts with little or no jamming. It has springs which provide six degrees of freedom between the wrist and the end effector. The suitable compliance of the hand can be generated by adjusting the stiffness of the six springs. The flexible manipulator has some compliance naturally due to flexibility of the beam, so that it may have the advantage of passive compliance.

As an alternate to passive compliance, an active compliance control scheme was presented by Salisbury [25]. In this scheme, the position gain matrix of a joint based servo system can be modified to have a certain stiffness of the end effector along the base cartesian coordinate system. It was suggested that the feedback gain matrix be calculated from the multiplication of the manipulator jacobian and the desired stiffness matrix of the end effector.

The nature of kinematics of the contact point at the instant of contact was formalized by Mason [10].

A combination of the conventional position feedback control and the explicit force control scheme called "the hybrid position force control" was suggested by Raibert and Craig [26]. Khatib [27] implemented that scheme with a PUMA 560 to control the contact force of the end effector using the COSMOS parallel processing system. West and Asada [28] designed the hybrid control scheme for the manipulator constrained by the contact of the jig hand. They showed an application to the constrained grinding robot in this paper and in West's thesis [11].

In this bracing manipulator research, the kinematics will be analyzed within the frame of Mason's work [10].

In order to brace the large arm smoothly, force control seems to be essential in addition to position control. Among several force control schemes, the mechanical impedance control of the end effector

appears adequate to brace on soft parts because it exhibits inverse stiffness of the environment. However, in the applications of a large flexible arm, the bracing surface is assumed to be stiff. Hybrid position and force control, applying explicit force control normal to the bracing surface, in combination with position control parallel to the surface is considered. The hybrid control is supposed to be useful for bracing a large flexible arm and sliding it along the constrained surface for suitable applications such as large structure welding. Since the large arm of a bracing manipulator has a natural compliance, the hybrid control will be designed considering the effect of the link's flexibility.

DISCUSSION AND CONCLUSION

The objective of this research is to explore staging in positioning, which is a new interpretation of a positioning task, with a specific example a bracing manipulator. The bracing effect is analyzed from the view point of reduction of uncertainty. However, the implementation of the bracing strategy will increase system cost and complexity of control. Therefore, the overall system performance index has to be defined to compare the performance of a bracing manipulator with that of an unbraced manipulator, and to express the effect of bracing and staging in position. The performance index will be expressed in terms of system positioning accuracy, travel time, speed, hardware cost, and complexity of control for a certain reference task. Then, the overall performance of the bracing manipulator will be evaluated comparing to the unbraced case. Through these procedures, the task area for which the bracing manipulator has an advantage over the unbraced manipulator will be determined.

Research is continuing in the following areas : experimental verification of 2 link flexible arm modeling, robust control of 2 link flexible arm, design of a bracing wrist with a force sensor, and control of the small arm at the end of the large arm. All of these research will contribute to the implementation of a bracing manipulator.

ACKNOWLEDGEMENT

This work is partially supported through grant number NAG 1-623 from the National Aeronautics and Space Administration and through the Computer Integrated Manufacturing System Program at Georgia Institute of Technology.

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